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Improving Post-Stall Airfoil Performance Using Synthetic Jet-Based Flow Control

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Abstract. This study numerically investigates the aerodynamic performance of a NACA0012 airfoil equipped with a leading-edge synthetic jet actuator at a Reynolds number of $1.35x10^5$. The analysis was conducted at a fixed angle of attack of 16° to represent post-stall flow conditions. Two-dimensional unsteady, incompressible Reynolds-Averaged Navier-Stokes equations were solved using a commercial finite-element solver, and the baseline results were validated against available experimental data. The effects of actuation frequency and jet velocity ratio on aerodynamic characteristics were examined. Results indicate that actuation frequency plays a dominant role in flow control effectiveness. At twice the natural wake frequency ($2f_c$), the synthetic jet substantially improved aerodynamic efficiency, increasing the lift-to-drag ratio by up to 34.1% compared to the baseline case. These findings demonstrate the strong potential of synthetic jet actuators for mitigating flow separation and enhancing post-stall performance in future low-energy aerodynamic applications.

Introduction

The global aviation industry, while facilitating rapid transportation and economic development, has also become a notable source of anthropogenic climate change. Recent analyses indicate that commercial aviation contributes about 2.4% of total global CO_2 emissions [1]. A considerable share of this impact originates from aerodynamic inefficiencies, particularly drag-induced fuel consumption during cruise flight [2]. Consequently, many studies have focused on improving aerodynamic performance by reducing drag and increasing the lift-to-drag ratio as part of a broader effort toward sustainable aviation.

Flow separation is among the key causes of aerodynamic inefficiency. It occurs when the boundary layer loses momentum and detaches from the surface under adverse pressure gradients, leading to a marked increase in pressure drag and loss of lift, especially at high angles of attack or during unsteady manoeuvres. Traditional passive flow control methods—such as vortex generators, winglets, and riblets—have been widely applied to alleviate flow separation; however, they lack adaptability to varying flow conditions and flight regimes [3]. In contrast, active flow control (AFC) techniques provide real-time control over the flow field. Among these, synthetic jet actuators (SJAs) have drawn significant attention as a compact, energy-efficient, and geometry-preserving solution [1,9]. By producing zero-net-mass-flux oscillatory jets, SJAs can re-energize the boundary layer and delay separation without requiring an external air supply [4]. These features make them highly suitable for sustainable aircraft applications, enabling performance enhancement with minimal design compromise [5,6]. The jet produced by an SJA is typically described by a sinusoidal velocity profile characterized by its peak jet velocity (U_{jet}) and actuation frequency (f_a).

This study presents a numerical investigation of an NACA0012 airfoil equipped with a single synthetic jet actuator using a commercial finite-element-based solver. The objective is to evaluate aerodynamic improvements, particularly the lift-to-drag ratio, under post-stall conditions. Although the broader motivation relates to the development of energy-efficient flow control

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strategies for emission reduction, the current work focuses on the aerodynamic effects at a single angle of attack of 16°.

Model, Computational Methods and Validation

The airfoil has a chord length (c) of 0.15 m and a free-stream flow Reynolds number of parallel to the experimental validation study by Lee and Gerontakos [7]. For the NACA0012 airfoil, incompressible Reynolds-Averaged Navier-Stokes (RANS) was solved over time numerically as the Mach number of the free-stream flow, $M_\infty < 0.3$. The numerical study utilized a 2-D geometry for the airfoil, and $k-\omega$ SST turbulence model was employed. A C-type grid was used with a size of 20c x 20c. The time step of the simulation is $\Delta t = 1\text{x}10^{-4}$, and the total time is set to t = 10 seconds. The solver is using a 2nd order accurate discretization for space and time. The lift and drag coefficients are the time-average values, disregarding the first second. A mesh grid independence test was conducted to ensure that the mesh grid does not affect the results.

Figure 1a illustrates the NACA0012 airfoil with mesh, and Figure 1b presents the illustration of the synthetic jet actuator, which is located near the leading edge of the upper surface, where the orifice mid-point is located at x/c = 5.33%. The synthetic jet actuator is modelled as a velocity boundary condition to mimic the piezoelectric diaphragm and has the same dimensions as reported in the work of Gungordu et al. [4,9].

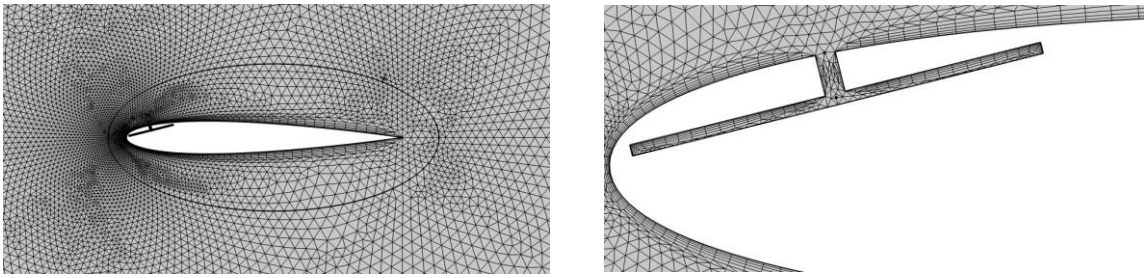

Figure 1: (a) NACA0012 Airfoil with mesh (left) (b) Magnified view of the synthetic jet actuator in the airfoil (right)

The base-flow (i.e., no flow control) lift coefficient results of the airfoil for various angles of attack at a Reynolds number of 1.35×10^5 were taken from the experimental study of Lee and Gerontakos [8]. The results revealed that the accuracy of the numerical study exceeds 95% across the entire angle-of-attack sweep when compared with the experimental data. For the present investigation, the angle of attack of the NACA0012 airfoil was fixed at α = 16°, at which a strong wake formation accompanied by vortex shedding is observed. By performing a power spectral density analysis of the wake using a virtual pressure probe, the characteristic vortex shedding frequency (f_c) was identified as 34.2 Hz. Accordingly, the oscillation frequency of the synthetic jet actuator was selected within this range. The synthetic jet actuation frequency (f_a) was varied as 0.5 f_c, f_c, and 2 f_c.

Results and Discussion

Table 1 summarizes the principal numerical results for the simulated flow-control cases at a fixed angle of attack of 16°. The reported parameters include the velocity ratio (V.R.; defined as the ratio of peak orifice-exit jet velocity to free-stream velocity), synthetic jet actuation frequency, lift-to-drag ratio, the corresponding baseline lift-to-drag ratio without flow control, and the relative percentage difference.

The aerodynamic performance of the airfoil exhibits a clear dependence on both the velocity ratio (V.R.) and the actuation frequency (f_a). At V.R. = 1.0, increasing the actuation frequency leads to a progressive improvement in the lift-to-drag ratio, with C_l/C_d increasing from 3.76 to

4.30, corresponding to a maximum enhancement of 7.1% relative to the baseline. As the velocity ratio increases to V.R. = 1.8, the influence of actuation frequency becomes more pronounced, with the maximum C_l/C_d reaching 5.28 at $2f_c$, representing a 34.1% improvement.

For both velocity ratio cases, actuation frequency of $0.5f_c$ provides only minor or negligible improvements, whereas the intermediate frequency (f_c) results in moderate gains. Overall, the results demonstrate that higher velocity ratios and higher actuation frequencies consistently produce stronger flow-control authority, leading to substantial improvements in aerodynamic efficiency, particularly at $f_a = 2f_c$.

Table 1: *Aerodynamic performance for different velocity ratios and actuation frequencies*

Case	V.R.	Actuation Frequency (f_a)	C_l/C_d	Baseline C_l/C_d	Difference (%)
1	1.0	0.5 f_c	3.76	3.94	−4.5
2	1.0	f_c	4.11	3.94	4.4
3	1.0	2 f_c	4.30	3.94	7.1
4	1.8	0.5 f_c	3.94	3.94	0
5	1.8	f_c	4.84	3.94	23.1
6	1.8	2 f_c	5.28	3.94	34.1

Conclusions

This numerical study investigated the aerodynamic effects of a synthetic jet actuator located at the leading edge of a NACA 0012 airfoil under post-stall flow conditions. The results demonstrate that the actuation frequency is the dominant parameter governing aerodynamic performance. At half of the characteristic wake frequency ($0.5\ f_c$), the actuator provided limited benefits and, in some cases, reduced the lift-to-drag ratio due to intensified vortex shedding. Near the characteristic frequency (f_c), moderate improvements of approximately 4–7% were observed. The most significant performance gains occurred when the actuation frequency was twice the wake frequency ($2\ f_c$), where the lift-to-drag ratio increased by up to 34.1% compared with the baseline case.

In the present study, the synthetic jet actuator was modelled using a prescribed velocity boundary condition at the orifice to emulate the oscillatory jet generated by a piezoelectric diaphragm. While this approach captures the primary aerodynamic effects of synthetic jet actuation, it does not fully represent the coupled structural–fluid–acoustic behaviour of a real piezoelectric actuator. Future work should therefore incorporate a fully coupled physical model of the piezoelectric diaphragm and cavity dynamics to provide a more realistic representation of actuator performance. In addition, extending the numerical framework to three-dimensional simulations would enable the investigation of spanwise effects, three-dimensional vortex structures, and their influence on flow-control effectiveness under realistic operating conditions.

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